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**COMPARISON OF UV ABSORPTION MEASUREMENTS WITH
PROBE-SAMPLING MEASUREMENTS OF NITRIC
OXIDE CONCENTRATION IN A JET
ENGINE COMBUSTOR EXHAUST**

ENGINE TEST FACILITY
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ARNOLD AIR FORCE STATION, TENNESSEE 37389

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AEDC-TR-76-134, September 1976
(UNCLASSIFIED REPORT)

COMPARISON OF UV ABSORPTION MEASUREMENTS WITH PROBE-SAMPLING MEASUREMENTS OF NITRIC OXIDE CONCENTRATION IN A JET ENGINE COMBUSTOR EXHAUST

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Errors have been found in the theoretical model as presented in Eqs. (1) through (6) on pages 11 through 13. Consequently, the data presented in Figs. 4, 5, 10, and 11 and Tables 1 and 2, obtained using the model, must be considered suspect.

An AEDC Technical Report containing the correct model and corrected data will be issued.

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) Measurements were made in the exhaust of a T-56 turbine engine combustor of nitric oxide (NO) concentration using an ultraviolet (UV) spectral absorption technique. The measurements were made at two axial locations in the combustor exhaust stream. The NO γ -band radiation at 2265 Å produced in a resonance source was passed through the exhaust stream, and the amount transmitted was recorded. The mathematical model used to determine the NO		

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20. ABSTRACT (Continued)

concentration from the absorption measurements is described. Pressure and temperature broadening effects on the measured absorption are considered in the line-by-line transmission calculation. The line-of-sight absorption measurements through the axisymmetric exhaust stream were converted to local concentration values via an iterative radial inversion computation. These in situ measurements are compared to NO concentration values obtained by conventional probe-sampling techniques using a chemiluminescent analyzer. The in situ measurements of the NO concentration were larger than the probe-sampled measurements by from 50 to 80 percent, depending upon the measurement location in the exhaust stream.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), at the request of the Air Force Aero-Propulsion Laboratory, Wright-Patterson AFB, Ohio, under Program Element 62203F. The experimental portion of this work was done at the Air Force Aeropropulsion Laboratory, Wright-Patterson Air Force Base, Ohio, from April 1 to June 15, 1975. The results of the research were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number R32P-A6A. The authors of this report were J. D. Few, W. K. McGregor, and H. N. Glassman, ARO, Inc. The manuscript (ARO Control No. ARO- ETF-TR-76-77) was submitted for publication on July 19, 1976.

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1.0 INTRODUCTION

The work reported herein is part of a program currently being conducted to assess the feasibility of employing optical techniques for the measurement of pollutant emissions from jet engine exhausts. The experimental portion of this work was conducted at the USAF Aeropropulsion Laboratory (AFAPL), Wright-Patterson Air Force Base, Ohio. The work reported here is concerned with the measurement of nitric oxide (NO) concentration using a previously developed ultraviolet (UV) resonance absorption method (Refs. 1 and 2). Other investigative efforts in this program are described in Refs. 3, 4, and 5.

An exhaust gas, similar to a turbine engine exhaust, was generated by use of a conventional jet engine combustor burning JP-4 fuel. The combustion gas generated by this facility was subjected to probe-sampling analysis methods in accord with recognized practices (Ref. 6) and to optical absorption methods. An infrared (IR) gas filter correlation method was employed by others for NO and carbon monoxide (CO) concentration measurements, and this work is reported separately (Ref. 4). The work reported here concerns only the measurements made using the UV resonance absorption method for determining NO concentration and the measurements of NO concentration made using a conventional gas-sampling probe and chemiluminescent-type gas analyzer.

The UV resonance absorption method, as used previously (Refs. 1 and 2), has been restricted to cases in which the concentration, static temperature, and static pressure along the optical path were assumed to be homogeneous. For the first time, a radial inversion of the distribution of measured transmissivity as a function of the distance from the stream centerline (hereafter referred to as the projected transmissivity distribution), along with knowledge of the radial static temperature distribution obtained by a total temperature probe and an assumed constant static pressure, permitted determination of local values of NO concentration so that a radial distribution of concentration was obtained. The local values of NO concentration obtained by the optical method are compared in the report to local values measured by probe sampling in conjunction with a chemiluminescent analyzer.

The combustor was operated at a constant fuel to air ratio of about 0.013, but on occasion pyridine was added to the fuel to increase the nitric oxide concentration and thus provide a range of measurement conditions. The combustor exhaust flowed through an 18-ft length of 12-in. - diam duct before exhausting to atmosphere. Measurements were made

at two axial stations in the combustor exhaust stream: 3 in. downstream of the duct exit, and about 18 in. downstream. The latter measurement station was chosen in order to test the optical methods in a nonhomogeneous medium.

2.0 EXPERIMENTAL APPARATUS

2.1 COMBUSTION GAS GENERATOR

The combustion gas generator apparatus consists of a heated inlet air supply and a fuel system from which JP-4 fuel is fed to a T-56 turbine engine combustor, which exhausts through a plenum section and through an exhaust duct 12 in. in diameter and approximately 18 ft long to atmosphere. The combustor was operated at an inlet air temperature of 900°F with a fuel to air ratio of 0.013, and the airflow rate through the combustor was 4.5 lb/sec for these tests. Ambient air is entrained in the plenum section and mixed with the combustor exhaust at the inlet of the 12-in. duct. The velocity of the gas at the duct exit was determined to be about 200 ft/sec. The optical and probe gas-sampling measurements were made at stations 3 and 18 in. downstream of the exhaust duct exit. A schematic diagram of the combustor and associated equipment is shown in Fig. 1. A more detailed description of the experimental setup is contained in Ref. 3.

In one phase of the program pyridine was added to the fuel in order to increase the NO content of the exhaust gas. The pyridine was added to the fuel by opening a needle valve to the pyridine supply bottle and setting a flow rate to give a certain amount of increase in the probe-measured NO concentration. Addition of the pyridine did not alter any of the performance parameters of the combustor by a significant amount (Ref. 3).

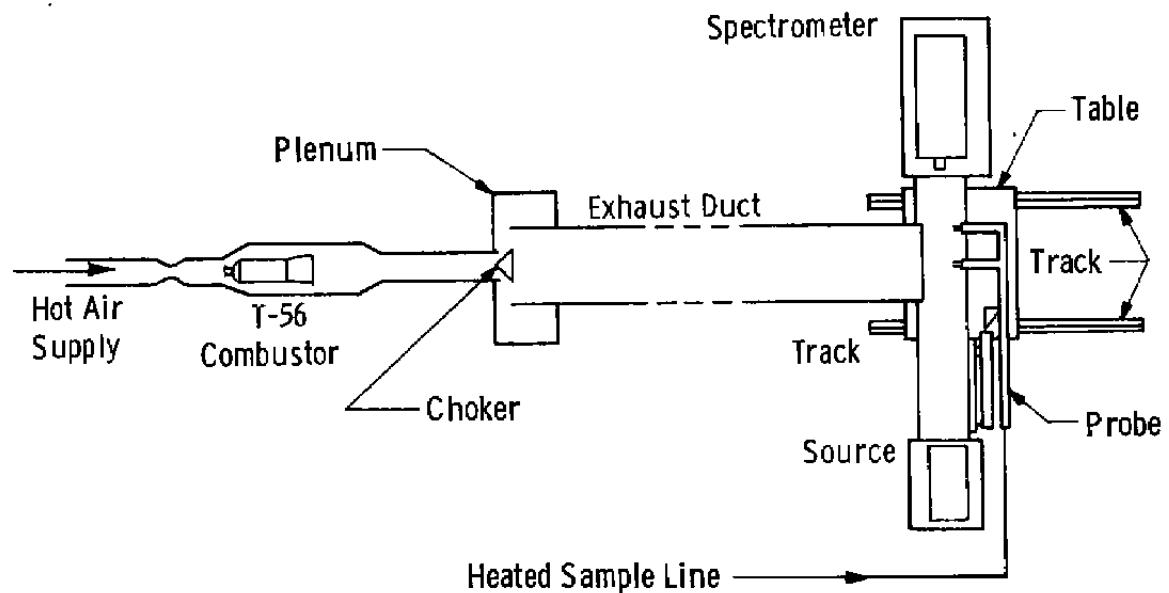
2.2 UV RESONANCE ABSORPTION SYSTEM

The in situ resonance absorption system, located as shown in Fig. 2, consisted of a resonance lamp source with transmitting optics and a 0.5-m spectrometer with receiving optics located on opposite sides of the exhaust duct on arms of a traverse mechanism which could be traversed vertically and positioned axially. The source optical system provided a 1-cm-diam parallel beam across the exhaust. The radiation source was a capillary, high voltage (3,000-v DC) discharge tube through which a 12:3:1 mixture

(by volume) of Ar:N₂:O₂, respectively, flowed at a pressure of 6 torr. The discharge tube was water cooled to lower the temperature of the gas mixture, thus ensuring a narrow line radiation source.

The spectrometer (receiver) used in this experiment was a 0.5-m Czerny-Turner type mount, grating instrument with a 2,360 groove/mm grating blazed for maximum reflection at 3,000 Å. The spectrometer was equipped with curved slits which were opened to 200 μ. The 200-μ slit width resulted in a 1.6-Å spectral bandpass. An RCA 1P28 photomultiplier tube, selected for low noise and high gain, was used as a detector. The photomultiplier tube signal was amplified by an operational amplifier, and the signal was recorded as the ordinate on an x-y plotter.

The conventional wavelength drive of the spectrometer was replaced by a Selsyn® motor receiver which could be driven by the Selsyn® driver located remotely in order to provide remote control of the wavelength. A 10-turn potentiometer was geared to the Selsyn® receiver shaft and provided the wavelength signal which was recorded as the abscissa on the x-y plotter.



**Figure 1. Diagram of combustor facility and instrumentation layout
(AFAPL System at WPAFB, Ohio).**

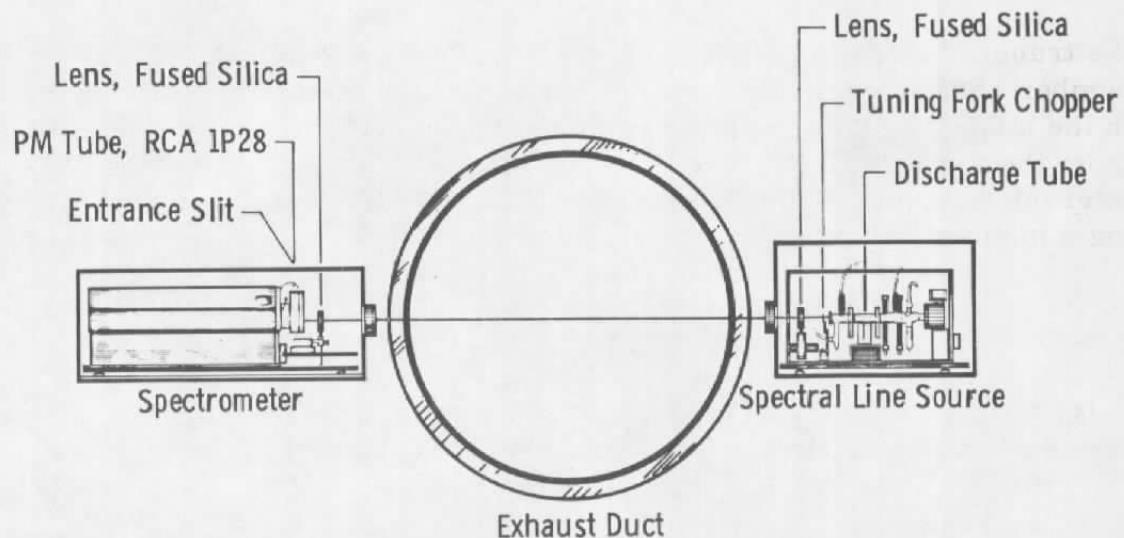


Figure 2. Schematic of resonance absorption apparatus for in situ measurements of NO concentration in exhaust of jet engine combustor.

2.3 PROBE-SAMPLING SYSTEM

The probe and gas-sampling system used for this study were constructed in accordance with recommendations by the Environmental Protection Agency (EPA) (Ref. 6). The probe tip was a section of 0.18-in. -ID uncooled stainless steel tube; the transfer line was an approximately 50-ft length of 0.25-in. stainless steel tubing heated by electrical heater tape to a temperature of 300°F; and the NO analyzer was a TEKO Model 10A chemiluminescent-type instrument. A total temperature probe, utilizing a Chromel®-Alumel® thermocouple was also mounted on the probe strut and was used to obtain total temperature profiles. Since the velocity is low (\approx 200 ft/sec), the static temperature in the exhaust stream was assumed to be equal to the measured total temperature.

3.0 DESCRIPTION OF THE UV RESONANCE ABSORPTION METHOD

3.1 THEORETICAL CONSIDERATIONS

The details of the theory of the UV resonance absorption technique for the measurement of species concentrations have been treated elsewhere (Refs. 7 through 9). The theory depicts the relationship between

the transmissivity at some wavelength and the properties (species number density, static temperature, and static pressure) of the gas in the absorbing path. For a radiation source emitting only radiation from the γ -bands of NO, the transmissivity, t , in a given frequency interval, $\Delta\nu$, of a homogeneous gas of a given pathlength, ℓ , containing a number density, N , of molecules is given by

$$t_{\Delta\nu} = \frac{\sum_j I_{\nu_j^0} \int_0^\infty \exp \left\{ - \left[\frac{2\sqrt{\ln 2} (\nu - \nu_j^0)}{(\Delta_s \nu_j)_D} \right]^2 \right\} \exp \left[- \frac{\ell}{\pi} \sum_i k_{\nu_i^0} \int_{-\infty}^{+\infty} \frac{a' e^{-y^2} dy}{a'^2 + (\omega_i - y)^2} \right] d\nu}{\sum_j I_{\nu_j^0} \int_0^\infty \exp \left\{ - \left[\frac{2\sqrt{\ln 2} (\nu - \nu_j^0)}{(\Delta_s \nu_j)_D} \right]^2 \right\} d\nu} \quad (1)$$

where:

$I_{\nu_j^0}$ = intensity of the j^{th} source line at center frequency, ν_j^0

ν = Frequency variable, cm^{-1}

$(\Delta_s \nu_j)_D$ = Doppler width at $1/2 I_{\nu_j^0}$ of the j^{th} source line, cm^{-1}

$$(\Delta_s \nu_j)_D = 2\nu_j^0 \sqrt{\frac{\ln 2 \kappa T_s}{M_s c^2}} \quad (2)$$

κ = Boltzmann's constant, 1.38×10^{-16} erg/ $^{\circ}\text{K}$

T_s = Gas temperature in the source lamp, $^{\circ}\text{K}$

c = Velocity of light, 3.00×10^{10} cm/sec

M_s = Mass of molecules in the source lamp, gm

$k_{\nu_i^0}$ = Doppler absorption coefficient of the i^{th} absorption line at line center frequency, ν_i^0 cm^{-1}

ℓ = path length, cm

a' = line-broadening parameter defined by

$$a' = 1,200 (\pm 200) p/T_a \quad (3)$$

p = static pressure in the absorbing medium,
atm

T_a = static temperature in the absorbing medium,
°K

y = dummy variable of integration

ω_i = Doppler frequency function for i^{th} line, at
frequency ν_i , given by

$$\omega_i = 2\sqrt{\ln 2} \frac{\nu - \nu_i^0}{(\Delta_a \nu_i)_D} \quad (4)$$

$(\Delta_a \nu_i)_D$ = Doppler width at $1/2 k_{\nu_i^0}$ of the i^{th} absorption line

$$(\Delta_a \nu_i)_D = 2\nu_i^0 \sqrt{\frac{2 \ln 2 \kappa T_a}{M_a c^2}} \quad (5)$$

T_a = static temperature of the absorbing gas, °K

M_a = mass of the molecules in the absorbing gas, gm

For the (0, 0) γ -bands of NO, the Doppler absorption coefficient at line center is related to the number density of absorbing molecules as follows:

$$k_{\nu_i^o} = 1.603 \times 10^{-14} \frac{S_i N}{T_a} \exp(-1.438 \frac{F_i}{T_a}) \quad (6)$$

where

N = number density of absorbing molecules, cm^{-3}

S_i = rotational line strength factor (Honl-London factor)

F_i = rotational energy of the ground state, cm^{-1}

The derivation of Equations (1) through (6) is given in detail in Refs. 8 and 9.

Equations (1) through (6) contain one optical quantity, the transmissivity t , and three gas properties, N , T_a , and p . The remainder of the terms are physical constants or known molecular properties. The pressure enters only as it affects the line-broadening parameter, a' . If the pressure and temperature are known, then N can be obtained from the measurement of the transmissivity, t . Note that the equation holds only when temperature, pressure, and concentration are constant along the optical path; however, if the properties of the gas are nonhomogeneous but the local radial values of N , T_a , and p are known, then the transmissivity can be calculated by summing along the path assuming increments, $\Delta\ell$, of homogeneous properties.

The inverse problem, determination of N along the optical path from measurements of t , T_a , and p along a path having nonuniform gas properties, can be solved in some cases. One such case is that of cylindrical symmetry in which concentric zones of constant properties can be assumed and a measurement of t is made through chords along the vertical direction, thus giving a projected transmissivity distribution as a function of distance from the stream centerline. The inversion procedure functions by starting with a transmissivity measurement in the outside zone, computing N from Eqs. 1 through 6, proceeding to the next zone and iterating on N of the inner zone until the measured t is determined, and so forth. In this way N as a function of the radial

distance is determined. More detail on the inversion procedure is given in Section 3.3.

3.2 PROCEDURE FOR OBTAINING UNIFORM GAS PROPERTIES IN ABSORPTION PATH

The procedure used to obtain the number of NO molecules along a given optical path is given as follows for the case of constant temperature and pressure of the absorbing gas along the path. The apparatus shown in Fig. 2 is used to obtain a reference trace of the spectrum of the (0, 0) γ -band of NO with no absorbing gas in the light path (that is, with the combustor off). Then, with the combustor operating, the spectrum is again scanned. An example trace is shown in Fig. 3 for the station 3 in. downstream of the combustion gas generator exit. It has been found convenient to use the transmissivity at the second bandhead of the (0, 0) band as a measure of the number of absorbing molecules in the path because of ease of measurement of the peak transmission. At gas temperatures less than about 1,000°K the transmissivity at the peak of either the (1, 1) or (2, 2) bands, which also appear in Fig. 3, serves as an indicator of whether attenuation from spurious sources (window fogging, source intensity change, particulate scattering, continuum absorption from other molecules, etc.) or drift in the source radiation needs to be accounted for in the determination of the transmissivity. In the case of Fig. 3, no appreciable difference in the transmission with the combustor on or off at the (1, 1) or (2, 2) bandheads can be detected, and no corrections to the (0, 0) second bandhead transmissivity need be made. If the ratio of the measured signal to the reference signal at the second bandhead of the (2, 2) band had been other than unity, the ratio at the (0, 0) bandhead would have been corrected by dividing it by that at the (2, 2) bandhead to obtain the transmissivity.

With the measured transmissivity, t , at a given combustor operating condition, it remains to relate the transmissivity to the optical thickness (number density times path length for uniform absorbers, Nl - molecules/cm²) of the absorbing gas. This relation may ensue from a calibration at temperatures and pressures expected; or, once the theoretical relations (1) through (6) are substantiated by experiment, the number density can be obtained from the first principle calculation. For the NO molecule a substantial amount of work has been done at AEDC to establish the first principle model (Ref. 9) so that the transmitted band profile can be accurately calculated for a given spectral instrument using a digital computer. Thus, the procedure used to

relate (0, 0) second bandhead transmissivity to number density along a uniform path is to input the temperature, the pressure, the path length, and several values of expected number density into a computer program for solving Eqs. (1) through (6), compute the spectra, and simulate the spectral measurement function. Shown in Fig. 4 are simulated (0, 0) band profiles for a range of number densities of NO at the path length and average pressure and temperature of the station 3 in. downstream of the combustor exhaust exit. The resulting transmissivity at the wavelength of the second bandhead is tabulated in Fig. 4, and the absorptivity, $\alpha (= 1 - t)$, is plotted as a function of the optical depth, $u_0 = N\ell$, in Fig. 5.

For purposes of pollutant emission measurements, the number density can be converted to parts per million by volume (ppmv) by dividing the number density of NO by the average gas number density at the given temperature and pressure. Figure 5 can then serve as a calibration plot, where the absorptivity, α , is plotted versus the optical depth (molecules/cm²), or concentration (ppmv) of NO. For example, the optical depth and concentration of NO corresponding to the data of Fig. 4 ($\alpha = 0.116$) is found from the calibration curve (Fig. 5) to be 53×10^{15} molecules/cm² ($\ell = 35.5$ cm, $N = 1.49 \times 10^{15}$ molecules/cm³), and the concentration is found to be 170 ppmv.

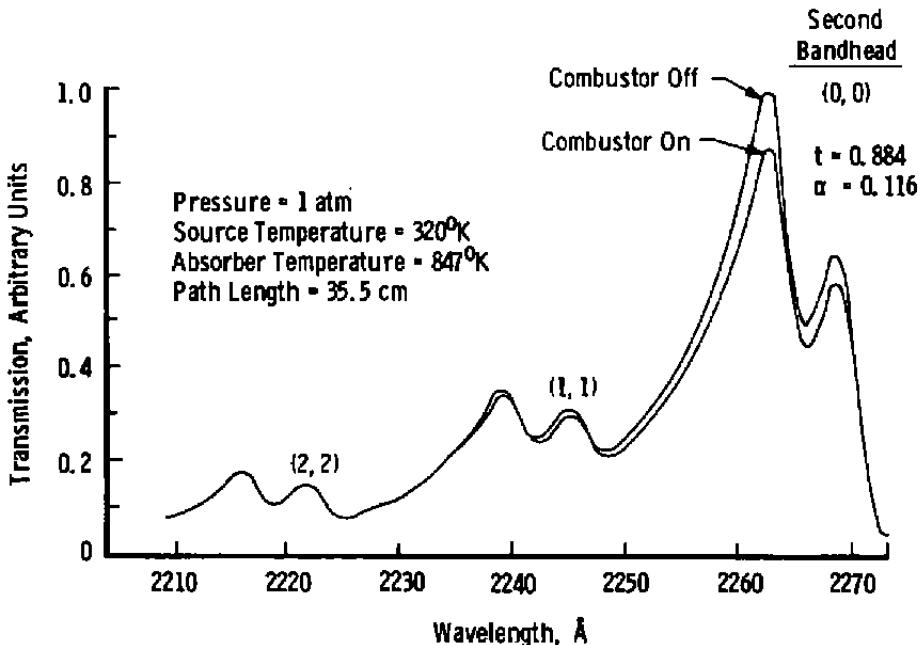
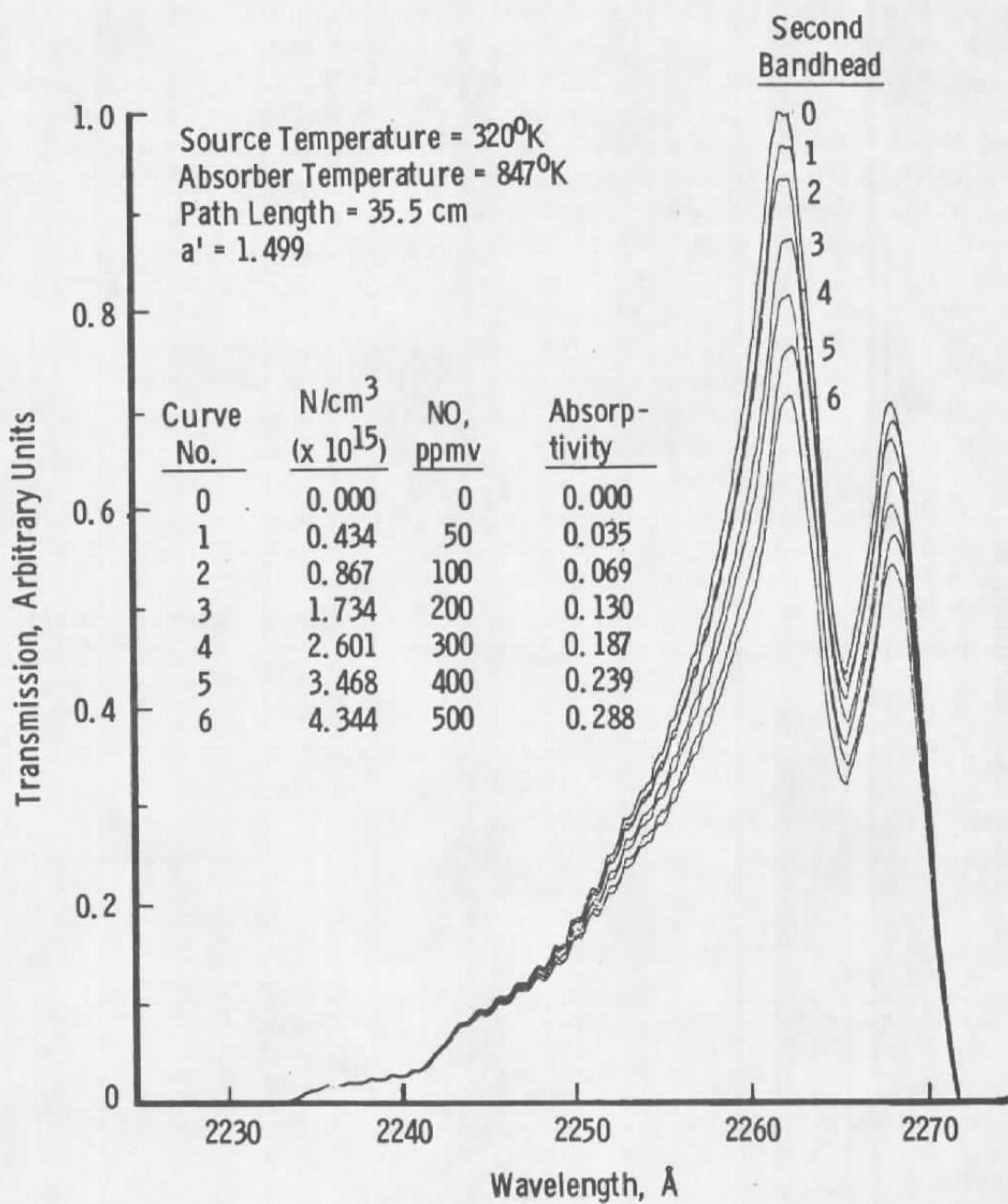


Figure 3. Measured transmission spectra of NO (0,0) γ -band at a station 3 in. downstream of combustor exhaust duct exit.

Figure 4. Simulated transmission spectra of NO (0,0) γ -band.

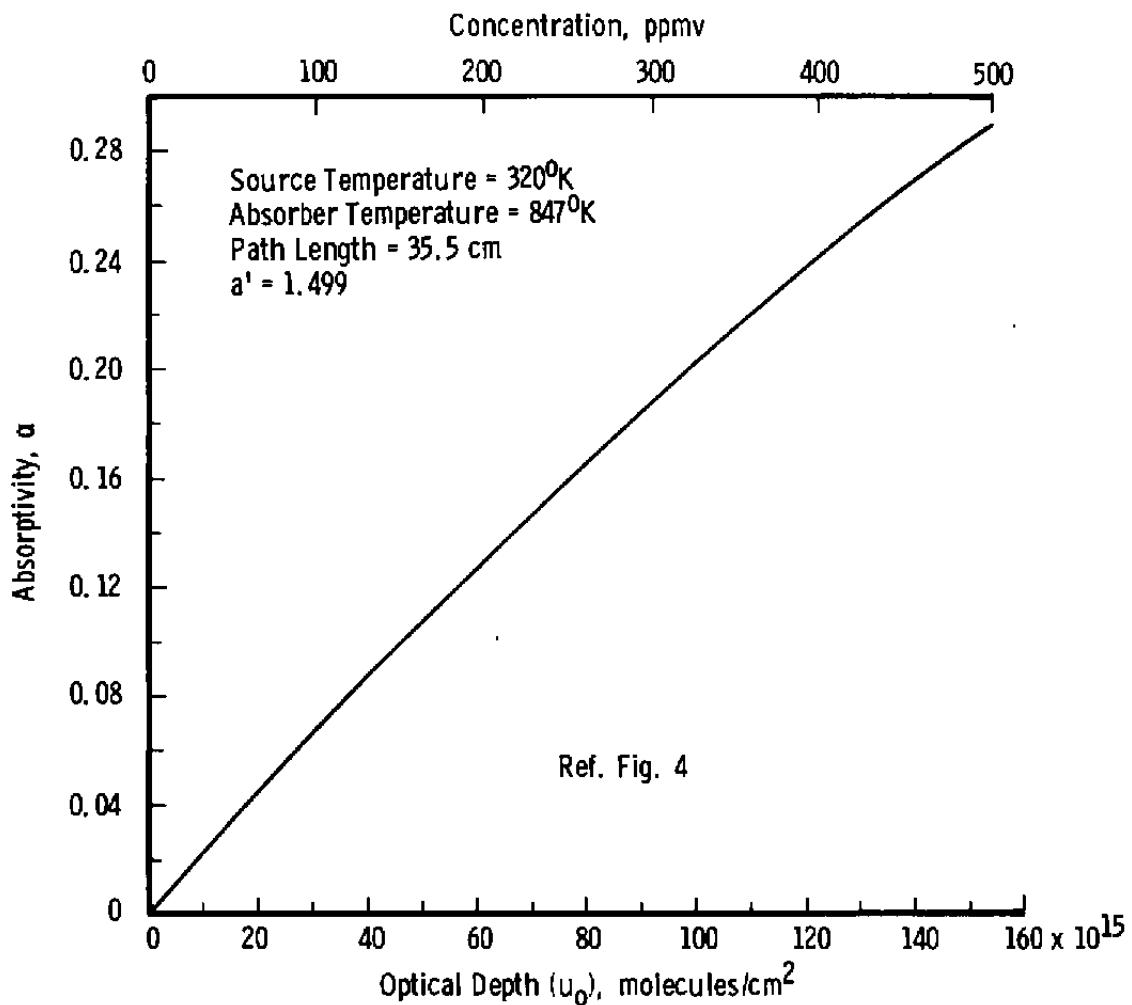


Figure 5. Calibration curve for second bandhead transmission of NO (0,0) γ -band.

3.3 PROCEDURE FOR OBTAINING NONUNIFORM GAS PROPERTIES IN ABSORPTION PATH

For the case of cylindrical symmetry the inversion procedure mentioned in Section 3.1 can be applied when the projected transmissivity distribution, $t(y)$, has been measured and $T_a(r)$ and $p(r)$ are known, as illustrated in Fig. 6. The radial total temperature distribution, $T(r)$, was measured using the total temperature probe with the assumption that in the low velocity stream (for example, 200 ft/sec) the static temperature was only slightly less than the total temperature. The static pressure profile, $p(r)$, was considered to be uniform and equal to the ambient pressure outside the stream, again because of the low velocity of the gas stream. An iterative computer program was written to accomplish the inversion of measured transmissivity data to the radial distribution of concentration, which proceeded as follows:

1. The cylindrical gas stream was divided into M concentric zones, and a known temperature, T_m , and known static pressure, p_m , were consigned to each zone, m (see Fig. 6).
2. The average path length of each zone for a given distance from the stream axis, y , was calculated from geometrical considerations and knowledge of the optical source beam size. It is important to note that the path length through each zone is a function of the radial station, m .
3. The number density of NO for the outer zone, $m = 1$, was calculated from the measured transmissivity and known T_1 and p_1 by iterating on Eqs. (1) through (6) until the computed transmissivity equalled the measured transmissivity. The number density in the second zone, $m = 2$, was then determined from the measured transmissivity, t_1 , and the known N_1 , p_2 , and T_2 in a similar manner.
4. In general, having found the number densities in the first $m-1$ rings, one can determine the number density in the m^{th} ring, and by this procedure the entire radial distribution of number density is obtained. Division of the number density by the local density as determined by the equation of state and knowledge of $T(r)$ and $p(r)$ then permits determination of the local concentration (expressed as ppmv).
5. The procedure in step (4) is repeated until the entire radial distribution is obtained.

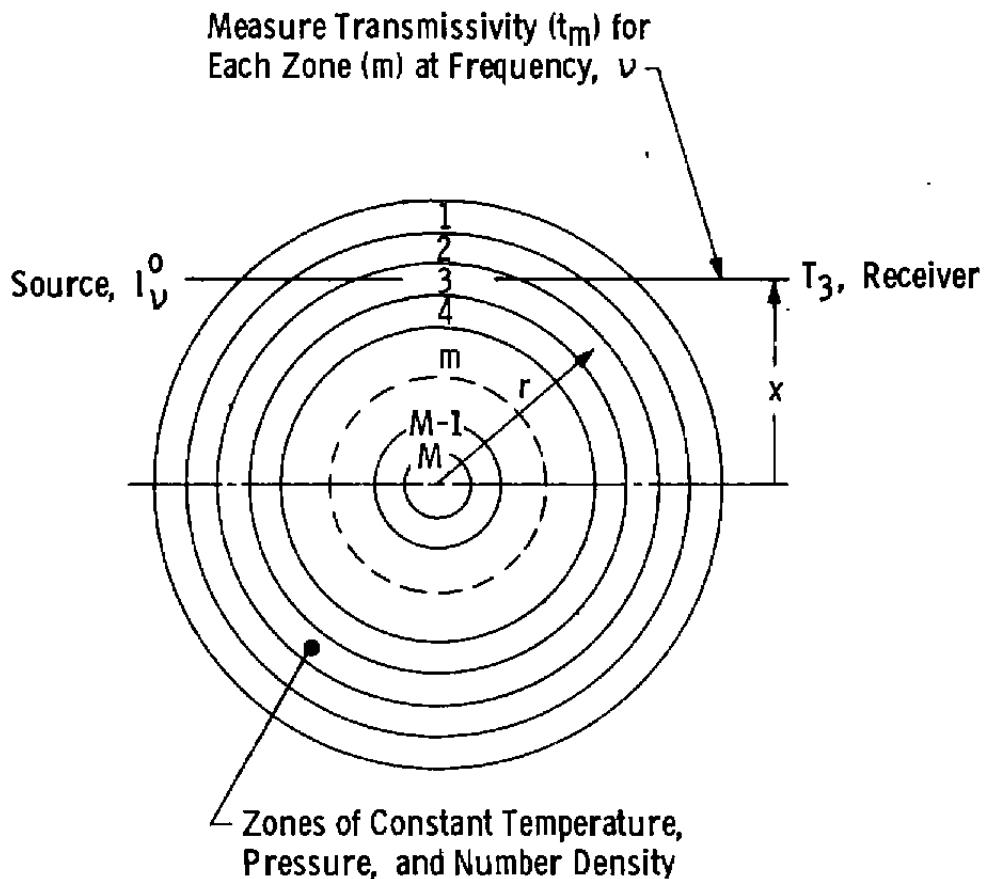


Figure 6. Illustration of radial inversion problem for determination of local concentration from transmissivity measurements.

3.4 METHODS OF COMPARISON OF OPTICAL ABSORPTION AND PROBE-SAMPLING MEASUREMENTS OF CONCENTRATION

The probe gas-sampling method of measurement gives a local concentration measurement of a specie; knowledge of the local static temperature and pressure permits the determination of a local number density of the specie from the concentration measurement. Optical measurements, on the other hand, are made of the transmissivity of the optical beam along a path through the flow stream; the transmissivity measurements are then related to the optical depth, u , defined by

$$u = \int_0^L N dl \quad (7)$$

where N is a variable along the path. An average number density, \bar{N} , can be found by dividing u by the path length, L . If an average temperature, \bar{T}_a , and pressure, \bar{p} , along the path are known, then an average concentration can be found by dividing N by the average total molecular

density. If several measurements of transmissivity are made through parallel chords of a cylindrically symmetric gas stream at various distances, y , from the axis, and the radial static temperature and pressure profiles are known, then the inversion procedure of Section 3.3 can be used to obtain local values of the number density of NO. In turn, the local density can be determined from the known static temperature and pressure, and the local concentration can be found by dividing the local value of NO number density by the local value of the total molecular density determined by the equation of state.

The statements in the above paragraph were meant to show that there is a serious problem in deciding on a basis for comparison of the probe-sampling and optical absorption results. This report uses four methods of comparison, which can be listed as follows:

<u>Method</u>	<u>Probe Sampling</u>	<u>Optical Absorption</u>
1.	Average Concentration, \bar{C} , determined over optical path length.	Average concentration determined from average static temperature and pressure, measured transmissivity, and experimentally determined path length.
2.	Optical depth computed from $\tau = \int_0^L C N_o dr$ with N_o determined from temperature and pressure measurements and C from sampling probe.	Optical depth determined by measured transmissivity and known average values of static temperature and pressure.
3.	Transmissivity computed from measured $N(r)$, $T(r)$ and assumed constant static pressure, by summing zonal transmissivities over small increments along the optical path.	Transmissivity measured.

4. Local concentration measured.

Local concentration computed from inversion of measured transmissivity using known $T(r)$ and assumed constant static pressure.

All these methods were used in comparing the results of the two measuring techniques used in this program. The last one, comparison of local values, is to be preferred because it provides the most direct comparison. However, when absorption data are available through only one path in the gas stream, one of the other methods must be used.

4.0 RESULTS

4.1 SAMPLING PROBE DATA

The gas-sampling probe and total temperature probe were used on all combustor runs either to determine radial profiles of temperature and emission species concentrations, or to obtain values at the centerline of the combustion gas generator exit. The combustor was operated at the same conditions for all the data presented, and both the probe measurements and the optical measurements attest to the repeatability of the combustor system exhaust gas properties (Ref. 3). In order to vary the nitric oxide concentration, pyridene was added to the fuel during some of the combustor runs; pyridene has the effect of increasing the NO concentration level in the exhaust gases. As stated previously, data were obtained for two types of radial profiles: a flat temperature and concentration profile at a station 3 in. from the combustion gas generator exit, and a bell-shaped profile caused by the mixing of the exhaust gas with ambient air at a station 18 in. (1.5 exhaust duct diameters) from the gas generator exit.

Radial distributions of concentration and temperature were obtained on several runs using the sampling and total temperature probes; repeatable results were generally obtained. The data to be used for comparison with the optical data are shown in Figs. 7 and 8 for the two types of profiles, flat and bell shaped. When pyridene was added to the fuel to increase the NO concentration, only centerline data were obtained. The average values of NO concentration and temperature obtained from Figs. 7 and 8 and the centerline values of concentration obtained when pyridene was added are given in Table 1. Note that there was no change in exhaust gas temperature when pyridene was added to the fuel.

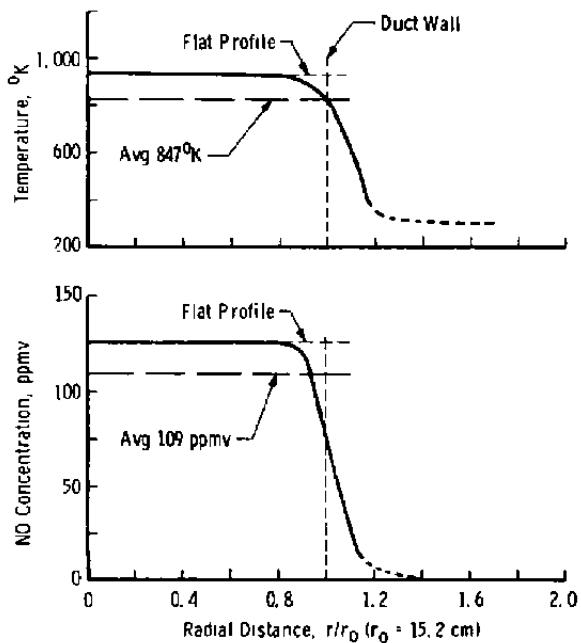


Figure 7. Probe measurement of total temperature and NO concentration at a station 3 in. downstream of combustor exhaust duct exit.

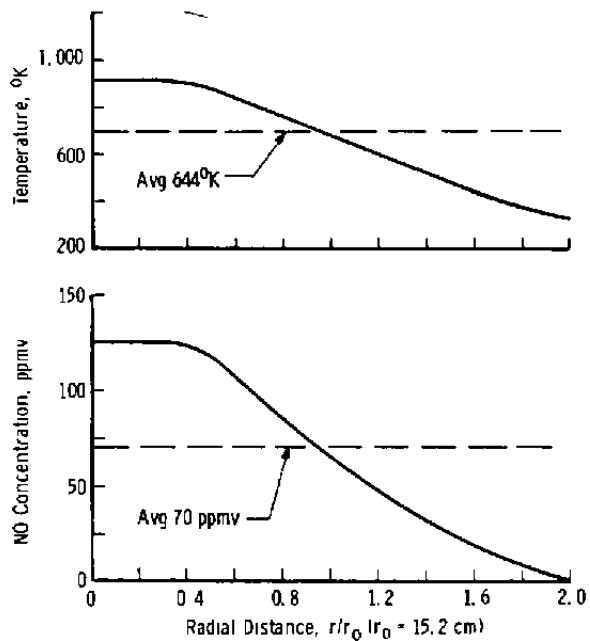


Figure 8. Probe measurement of total temperature and NO concentration at a station 18 in. downstream of combustor exhaust duct exit.

Table 1. Summary of NO Concentration Data Obtained from Probe Sampling and the UV Absorption Method Using an Average Temperature

Condition	Average Temperature, °K	Average NO Concentration Sampling Method, ppmv	NO Concentration UV Optical Method Average Temperature, ppmv	Average NO Concentration UV Optical Method Inversion, ppmv
1a: 3 in. Downstream	847	109	170	178
1b: 3 in. Downstream (Pyridene)	847	125	190	---
1c: 3 in. Downstream (Pyridene)	847	143	240	---
1d: 3 in. Downstream (Pyridene)	847	154	270	---
2: 18 in. Downstream	644	70	79	114

4.2 UV RESONANCE ABSORPTION DATA (NO)

The UV resonance absorption system was used to obtain data for all the conditions listed in Table 1. The absorption data taken at a fixed point on the centerline are presented in Fig. 4. The single path absorption data at the second bandhead were reduced to number density and concentration by using the average temperature obtained from the total temperature probe measurements and a path length determined from the concentration profiles obtained by the sampling probes, and by assuming a constant pressure equal to the barometric pressure for the particular run. The results of the single path absorption data on the basis of NO concentration are given in Table 1. Note that the values of NO concentration obtained by the absorption method average about 60 percent larger than the gas-sampling probe results at the 3-in. station. At the downstream station (18 in.) the average concentrations determined by the two methods are much closer; however, this result is deceiving, and use of an average temperature is not satisfactory in the resonance absorption technique, as will be shown in the following paragraphs.

Comparison of sampling probe and optical absorption measurements can also be made if both measurements are expressed in optical thickness, u , as defined in Eq. (7). The data of Figs. 7 and 8 were converted to u using point-by-point integration, Eq. (7), and the results are given in Table 2. Two columns of probe results are shown for comparison: column 2 (u_F) was obtained by assuming a flat profile extending to the duct wall at the 3-in. station as shown in Fig. 7, and column 3 (u_I) is the result of integrating Eq. (7) for the curves of Figs. 7 and 8. For the cases where pyridine was added, the u_I were determined by assuming the same relative concentration profile as when no pyridine was added.

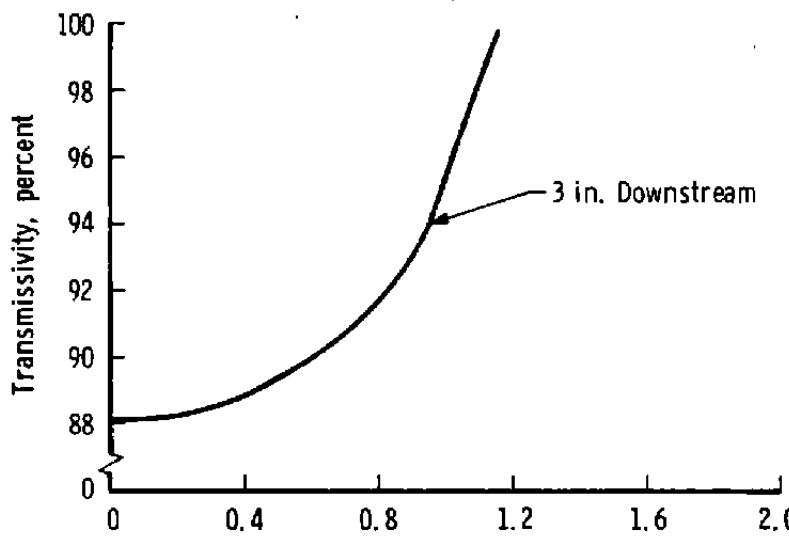
but with the maximum value as measured at the centerline. The single pass centerline optical absorption data can also be expressed as u if an average temperature is used. The average temperature obtained from the thermocouple probe data, Fig. 7, were used to determine the values of optical thickness (u_0) shown in column 4. Again it is noted that the measured optical value of u is considerably larger than would be predicted from the probe data.

Table 2. Comparison of Optical Measurements of NO Concentration with Probe Measurements

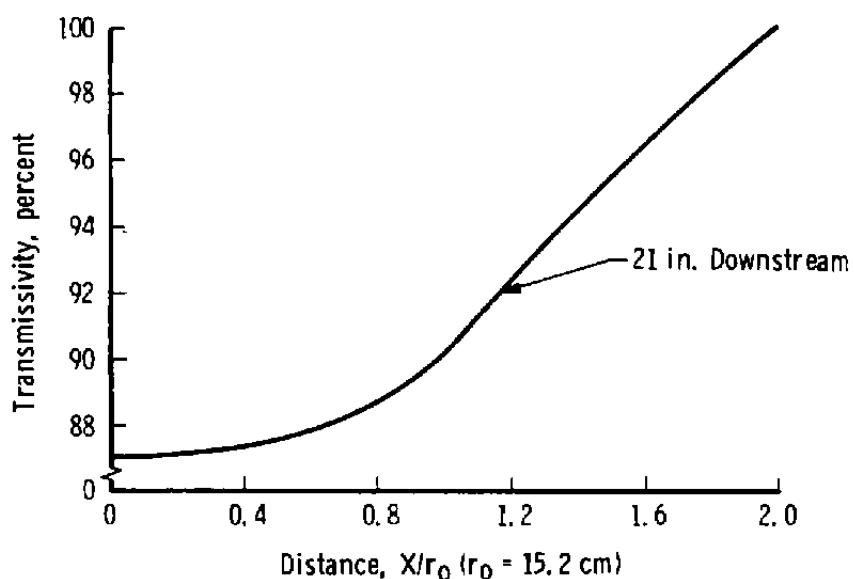
Condition	Optical Thickness, molecules/cm ² x 10 ¹⁵				Transmissivity, percent	
	Probe, Flat Profile, u_F	Probe, Integrated Value, u_I	Optical Method, Average Temperature, u_0	Optical Method, Inversion, u'_0	Calculated Transmissivity from Probe, t_p	Measured Transmissivity Optical Method, t_0
1a 3 in Downstream	30.5	32.8	53	57.8	93.5	88.4
1b 3 in Downstream (Pyridene)	35.0	38.2	59	----	----	87.5
1c 3 in. Downstream (Pyridene)	40.0	43.4	72	----	----	85
1d 3 in Downstream (Pyridene)	43.2	46.2	83	----	----	83
2 18 in Downstream	----	40.1	54	65.3	91.6	87.4

A third method of comparison of the probe-sampling and optical method of measurement is to compute the transmissivity, t , using the probe data, $N(r)$ and $T(r)$, of Figs. 7 and 8, in Eqs. (1) through (6). This calculation requires use of the computer program to compute t values for small segments of the path and to sum all the incremental values along the optical path. Calculation of the transmissivity through the centerline of the combustion gas stream was performed for cases 1a and 2, shown in Table 1, and the results are given in column 6 of Table 2. The measured transmissivity at the second bandhead for all the cases is given in column 7 of Table 2. The computed values of the centerline transmissivity from the probe data are considerably greater than the measured values. This variation is consistent with the indication of a larger value of the density of NO in the stream by the optical method than is indicated by the probe measurements.

For cases 1a and 2 (see Table 1), spatial scans of the absorption through chords of the exhaust gas stream with the spectrometer setting on the second bandhead peak were made to determine the projected transmissivity distribution, $t(y)$. The transmissivity data are shown in Fig. 9 for the two axial stations, and the results of inverting the transmissivity distribution to local values of the NO number density and the concentration are given in Figs. 10 and 11. For comparison, the local



a. 3 in. downstream



b. 18 in. downstream

Figure 9. Measured transmissivity profiles, using the second bandhead of the (0,0) γ -band of NO downstream of combustor exhaust duct exit.

values of NO concentration obtained from the sampling system are also shown in Figs. 10 and 11. The probe values of density or concentration are less than the optically obtained values all along the path; the factor ranges from about 1.8 at the center to about 1.5 near the edge of the stream. The average values of concentration obtained from Figs. 10

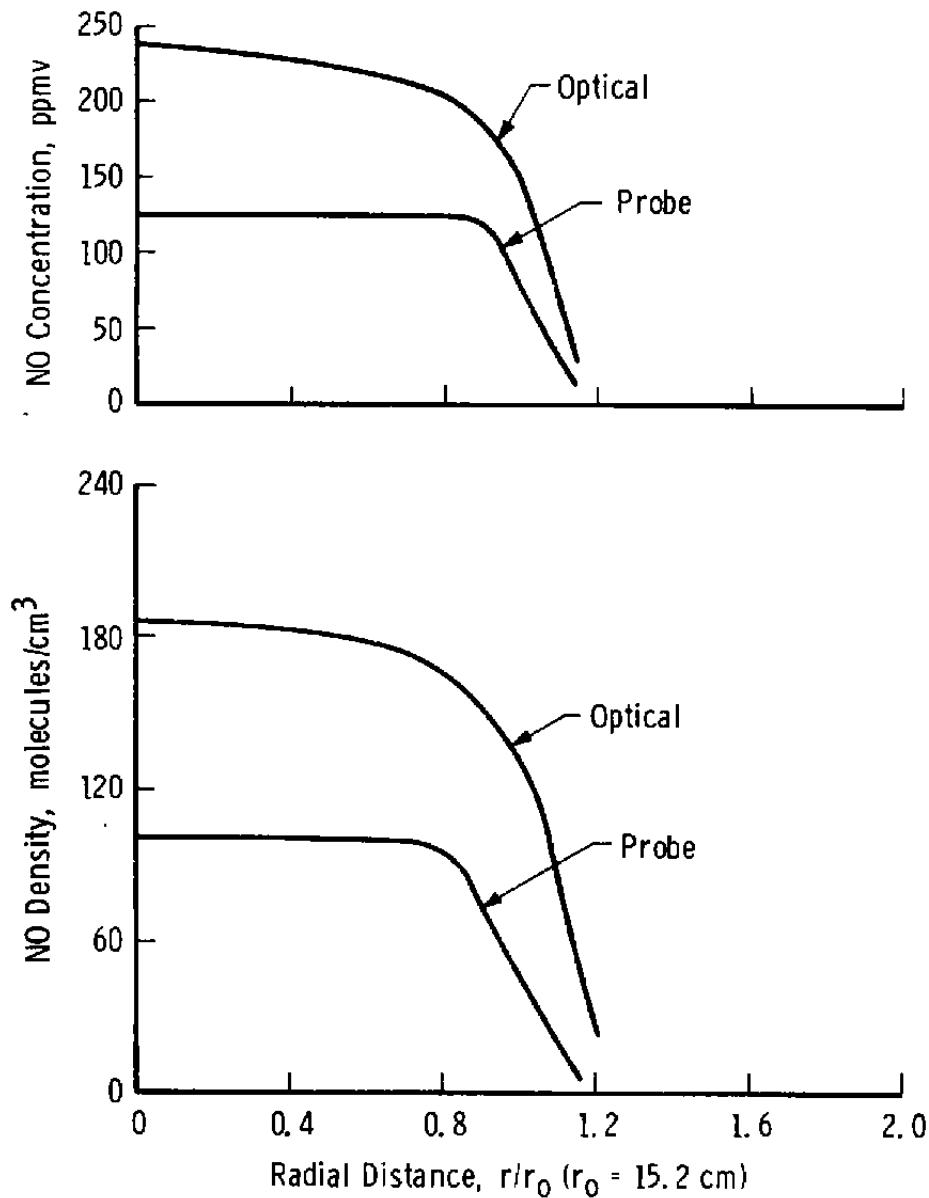


Figure 10. Results of inverting the transmissivity profile of Fig. 9a to local values of NO density and concentration compared to probe-measured values at a station 3 in. downstream of combustor exhaust duct exit.

and 11 are given in column 5 of Table 1. Note that at condition 2 the average (114 ppmv) from the inversion is much greater than the average obtained from a single pass measurement using an average temperature (79 ppmv). The point-by-point method of comparison is believed to be the most meaningful, but it requires considerably more effort and can

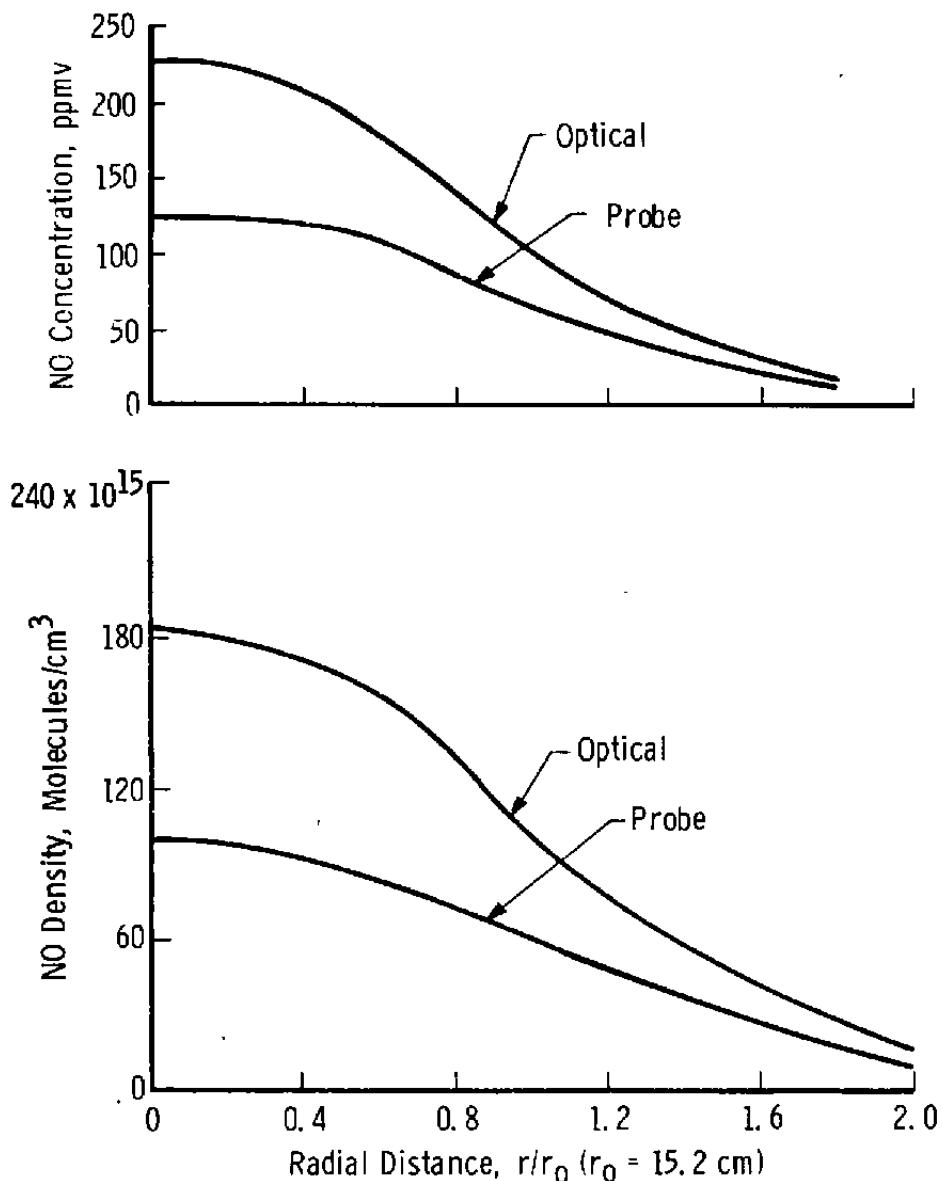


Figure 11. Results of inverting the transmissivity profile of Fig. 9b to local values of NO density and concentration compared to probe-measured values at a station 18 in. downstream of the combustor exhaust duct exit.

be done only for symmetric cases. A value of u_o' was also calculated from the inverted profiles of the number density of Figs. 10 and 11 for the two stations. These values are also given in Table 2 in column 5 as u_o' . Note here that there is a considerable difference between u_o' as determined by an average temperature and u_o' as determined using the more correct inversion data.

5.0 DISCUSSION

5.1 BASIS FOR COMPARING OPTICAL AND PROBE RESULTS FOR NO CONCENTRATION

Transmission of resonance radiation through a medium depends in a complicated way on the temperature along the optical path, as evidenced in Eqs. (1) through (6). The dependence of transmissivity on pressure enters only in the determination of the broadening parameter a' , and for the temperatures encountered in combustion gas streams the effects of pressure on the transmissivity are small. For this reason, the assignment of an "average concentration" (ppmv) or an "equivalent optical thickness" (molecules/cm^2), based on an average temperature, to a given transmission measurement in situations with large temperature variations along the path may be misleading. The data in Tables 1 and 2 for the downstream station, condition 2, attest to this statement. (For example, the concentration determined by use of an average temperature in the resonance absorption method given in Table 1 for condition 2 is 79 ppmv, which compares well with the probe-measured concentration; however, the average concentration obtained from inversion of the projected transmissivity distribution, Fig. 11, is 114 ppmv.) A similar statement can be made regarding comparison on the basis of the optical thickness. (For example, in Table 2, for condition 2, the optical thickness based upon an average temperature is 54×10^{15} molecules/cm 2 , whereas for the integration along the path using the inverted values of the number density the value is 65.3×10^{15} molecules/cm 2 .) Thus, for an optical method in which the transmission along a nonuniform optical path is dependent upon the temperature, the basis for comparison with probe-sampled results should be on a point-by-point basis in order to be meaningful.

5.2 UNCERTAINTIES IN RESONANCE ABSORPTION MEASUREMENTS OF NO CONCENTRATION

A reliable value of uncertainty can be placed on the resonance absorption measurement of NO number density or concentration only in the case of a homogeneous path of known static temperature and static pressure. The only parameter (other than the measurement uncertainty in t) to which an uncertainty can be ascribed in this study is the broadening parameter, a' . In this case the bias uncertainty in the broadening

parameter of ± 15 percent introduces a maximum uncertainty in the measured concentration of about ± 10 percent when the parameter (a') is between 0.5 and 2, which covers the range in a' encountered in this study. This uncertainty overshadows instrument and measurement uncertainties.

The propagation of uncertainty through the radial inversion of the measured transmissivity distribution to a radial concentration distribution is a complex process and requires a variance, covariance analysis for proper treatment. This work has not been done for the inversion discussed here, but work of a similar nature which can be extended to the resonance absorption case appears in Ref. 10.

The repeatability for eight different combustor runs of the transmission through the gas stream centerline at the 3-in. station made on different days during this program is shown in Table 3. Reflected in Table 3 are both the combustor facility repeatability and the instrument precision, which cannot be separated. The repeatability is considered very good and well within the bias uncertainty limits caused by the uncertainty in the broadening parameter, a' .

Table 3. Repeatability of Optical Transmission Data for T-56 Combustor Test

<u>Run No.</u>	<u>Percent Transmission</u>
1	88.4
2	88.5
3	88.3
4	88.7
5	88.4
6	88.4
7	88.7
8	88.4

6.0 SUMMARY OF RESULTS

The more relevant results obtained in this study may be listed as follows:

1. The feasibility of making NO concentration measurements in jet engine combustor exhausts using an optical UV absorption method was satisfactorily demonstrated.
2. The NO concentration, number density, or optical thickness determined from the UV resonance absorption measurements is larger by about 50 to 80 percent than similar values determined by probe-sampling techniques for a low velocity (≈ 200 ft/sec) combustion gas stream at a fuel to air ratio of about 0.01. This result is in substantial agreement with previous studies.
3. The radial distribution of NO number density, or concentration, was obtained successfully from measured distributions of the integrated transmission through a cylindrically symmetric gas stream. The computational technique to accomplish this radial inversion was developed during this study.
4. Comparison of optical and probe measurements must be made for either homogeneous optical paths, or point by point, radially inverted local number densities when the optical method depends upon the static temperature and pressure, in order for the comparison to be meaningful.

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